Transient Propagation in Lossy Coplanar Waveguides

Chun-Lin Liao, Yu-Ming Tu, Jeng-Yi Ke, and Chun Hsiung Chen, *Fellow, IEEE*

***Abstract*—Propagation of picosecond Gaussian and rectangular pulses along a lossy coplanar waveguide is investigated in detail. To this end, a new empirical formula for attenuation constant is proposed for discussing the conductor and leakage losses associated with the coplanar waveguide in which the thickness and conductivity of signal strip and ground planes are finite. This formula is obtained by comparing the results by the modified spectral-domain approach with those by the previous empirical formulas. Based on this new empirical formula, an efficient time-domain propagation model is established and applied to analyze the transient characteristics of Gaussian and rectangular pulses propagated along a lossy coplanar waveguide. In particular, the transient propagated pulses calculated by different empirical formulas are discussed and compared with those of the experimental data.**

I. INTRODUCTION

MODERN development of high speed devices and optical detection techniques necessitates a more accurate time-domain propagation analysis of transmission lines. In high speed circuits of transmitting picosecond pulses, the signal frequency spectrum may extend to the terahertz regime. Thus, one needs to accurately characterize and efficiently model the propagation constants of transmission lines even up to the terahertz range.

Transient propagation analysis of planar transmission lines is a topic of current research. The propagation modes of different coplanar waveguides were discussed by Riaziat *et al.* [1]. Based on the full-wave results, an emperical formula for effective dielectric constant was proposed for coplanar waveguides [2]. The leakage and radiation losses associated with a superconducting transmission line were demonstrated by [3] and [4]. Under a quasistatic assumption, an analytical formula for the radiation loss was established [5]. By these formulas, a transient propagation analysis of superconducting striplines has been conducted [6]. Further studies on the striplines suggested that the radiation loss is the main contribution of attenuation in the high frequency [7]. This radiation loss formula was modified to better fit the leakage attenuation phenomenon in high frequency range [8]. A propagation model including the radiation loss and conductor loss of coplanar waveguides was proposed and also compared with the experiment [9]. The factors such as geometry parameters and structure discontinuities to affect the transient propagation characteristics of coplanar waveguides were examined theoretically and experimentally by [10]. Recently, the technique of

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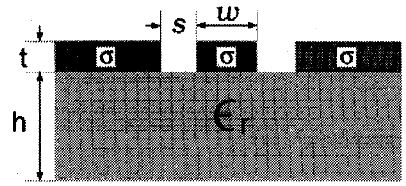


Fig. 1. Cross section of coplanar waveguide. (The dimensions shown in Figs. 1–11 are not in proportion to the actual ones.)

using the suspended coplanar waveguides [11], and the use of thin [12] and low [13] permittivity substrates were proposed to reduce the dispersion effect of planar transmission lines.

In comparison with the microstrip line, the coplanar waveguide structure is relatively low dispersion and thus receives much attention in monolithic microwave integrated circuits and high speed applications. The main contribution of attenuation in coplanar waveguide comes from the conductor and leakage losses. The leakage attenuation constant increases very rapidly as frequency increases and it eventually becomes the dominant one in determining the attenuation when the frequency is over several hundred gigahertz. The leakage loss has been theoretically characterized under the assumptions of perfectly electric conductor and infinitely thick substrate and can be approximated represented by a radiation empirical formula [8]. In the frequency range in which the leaky wave of coplanar waveguide is not excited, the conductor loss is the main source of attenuation which has been computed by the time-consuming modified spectral-domain approach [14]–[16].

To give an efficient time-domain propagation model, a new empirical formula for attenuation constant is proposed for discussing the conductor and leakage losses associated with the coplanar waveguide in which the thickness and conductivity of signal strip and ground planes are finite. Based on this new empirical formula, the transient propagation characteristics of Gaussian and rectangular pulses along a lossy coplanar waveguide are investigated in detail. Also included are the simulated pulses by several empirical formulas and those by measurement so as to support the usefulness of the new propagation model.

II. FORMULATION

The transient propagation phenomenon associated with the coplanar waveguide as shown in Fig. 1 is the main concern of this study. This coplanar waveguide has a dissipated signal strip and ground planes, of thickness t and conductivity σ, which are over a lossless substrate of thickness h and dielectric constant ϵ_r. The characteristic impedance of coplanar waveguide may be determined by the strip width w and the slot width s between signal strip and ground plane. Let an

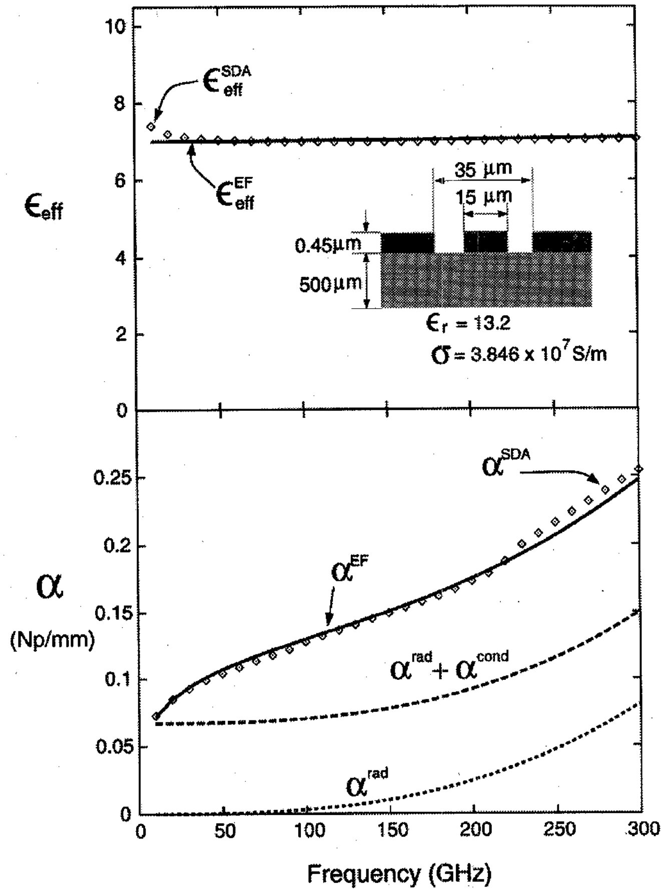


Fig. 2. Comparison of effective dielectric constants ϵ_{eff} and attenuation constants α by modified spectral-domain approach (SDA) and those by different empirical formulas.

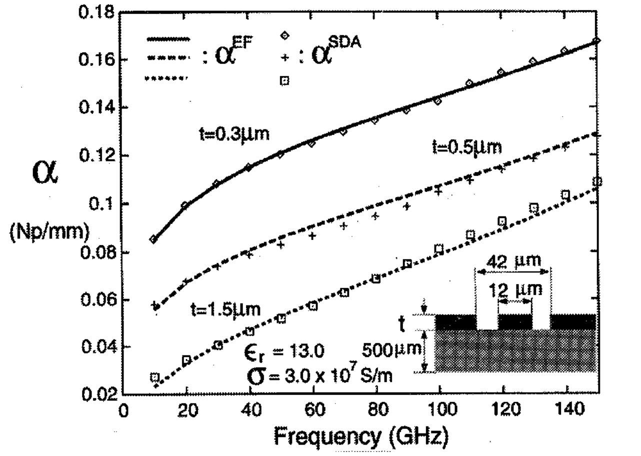
input pulse $V(0, t)$ be excited at the position $z = 0$. After propagating a distance z, the propagated pulse $V(z, t)$ at z can be dealt with by the technique of Fourier transformation [6] and [7]

$$V(z, t) = \text{IFT}\{e^{-\gamma(f)z}\,\text{FT}[V(0, t)]\} \tag{1}$$

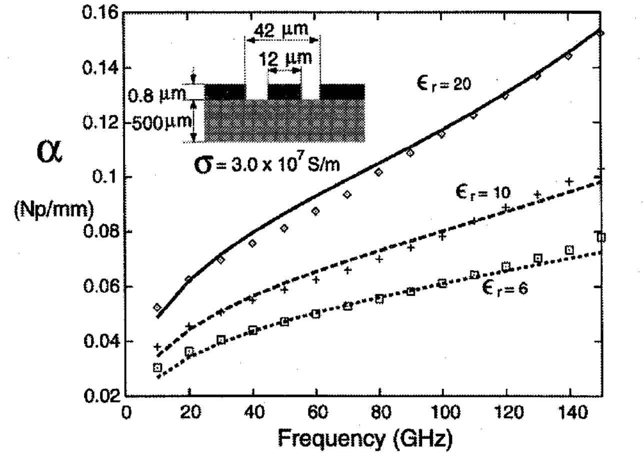
where FT and IFT are the direct and inverse Fourier transforms, respectively. To provide an efficient time-domain propagation model, the propagation constant of the coplanar waveguide ($\gamma = \alpha + j\beta$), which includes the attenuation constant α and phase constant β, should be accurately and effectively characterized even up to the terahertz range. The propagation constant is frequency-dependent and can be computed, numerically, by the time-consuming full-wave techniques such as the modified spectral-domain approach [14]–[16]. For design purpose, it is better described by the analytical empirical formulas.

A simple empirical formula [2] for effective dielectric constant ϵ_{eff}^{EF} has been proposed for a coplanar waveguide

$$\sqrt{\epsilon_{eff}^{EF}(f)} = \sqrt{\epsilon_q} + \frac{\sqrt{\epsilon_r} - \sqrt{\epsilon_q}}{(1 + aF^{-b})}. \tag{2}$$



(a)



(b)

Fig. 3. Attenuation constant α versus frequency with (a) metallization thickness t and (b) substrate dielectric constant ϵ_r as parameters.

Here $\epsilon_q = (\epsilon_r + 1)/2$, $F = f/f_{te}$, $f_{te} = c/4h\sqrt{\epsilon_r - 1}$ is the cutoff frequency of the TE_1 mode, $b = 1.8$,

$$\begin{aligned} \log(a) &= u \log\left(\frac{w}{s}\right) + v \\ u &= 0.54 - 0.64q + 0.015q^2 \\ v &= 0.43 - 0.86q + 0.540q^2 \end{aligned}$$

and $q = \log(w/h)$. This formula (2) was obtained under the assumptions of infinitely thin conductors and infinity conductivity.

Accurate values of effective dielectric constant $\epsilon_{eff}^{\text{SDA}}$ and attenuation constant α^{SDA} were available by the modified spectral-domain approach [14]. But this approach is too time consuming to be a practical tool for time-domain analysis.

Physically, the attenuation constant of coplanar waveguide in higher frequency range is mainly due to the leakage, and it has been approximately represented by the radiation empirical formula [8],

$$\alpha^{\text{rad}} = \left(\frac{\pi}{2}\right)^5 2 \left\{ \frac{\left[1 - \frac{\epsilon_{eff}(f)}{\epsilon_r}\right]^2}{\sqrt{\frac{\epsilon_{eff}(f)}{\epsilon_r}}} \right\} \frac{(w + 2s)^2 \epsilon_r^{3/2}}{c^3 K'(k) K(k)} f^3 \tag{3}$$

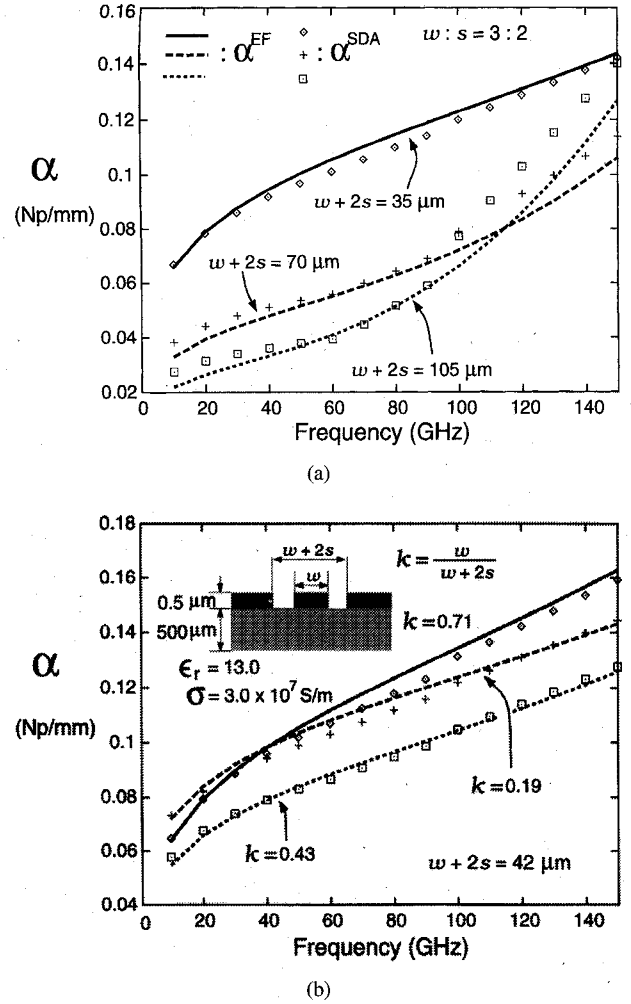


Fig. 4. Attenuation constant α versus frequency with (a) total width $(w+2s)$ and (b) the ratio $w/(w+2s)$ as parameters.

where $k = w/(w+2s)$, $K(k)$, and $K'(k)$ are the complete elliptic integrals of first kind and second kind, respectively. This radiation formula was derived under the assumptions of infinitely thick substrate as well as zero metallization thickness and infinity conductivity. Under the assumption of infinite substrate thickness, the leakage is in the form of radiation which occurs at all frequencies. But for the case with finite substrate thickness, the leakage is due to the leaky surface wave which occurs only above some specific frequency. Therefore, the formula (3) is applicable only for the case with very thick substrate.

In the frequency region in which the leaky wave of coplanar waveguide is not excited, the attenuation constant is mainly associated with the conductor loss which has been approximated discussed by a simple analytical formula [17],

$$\alpha^{cond} = 4.88 \times 10^{-4} R_s \epsilon_q Z_0 \frac{P}{\pi s}\left(1 + \frac{w}{s}\right) \times \left\{ \frac{1 + \dfrac{1.25t}{\pi w} + \dfrac{1.25}{\pi} \ln \dfrac{4\pi w}{t}}{\left[2 + \dfrac{w}{s} - \dfrac{1.25t}{\pi s}\left(1 + \ln \dfrac{4\pi w}{t}\right)\right]^2} \right\} \tag{4}$$

where R_s is the real part of the surface impedance of the conductor and Z_0 is the characteristic impedance of coplanar waveguide. The constant P in (4) is

$$P = \left[\frac{K(k)}{K'(k)}\right]^2 Q$$

where

$$Q = \frac{k}{(1 - \sqrt{1-k^2})(1-k^2)^{3/4}}, \qquad 0 \le k \le 0.707$$
$$= \frac{1}{(1-k)\sqrt{k}} \left[\frac{K'(k)}{K(k)}\right]^2, \qquad 0.707 \le k \le 1.$$

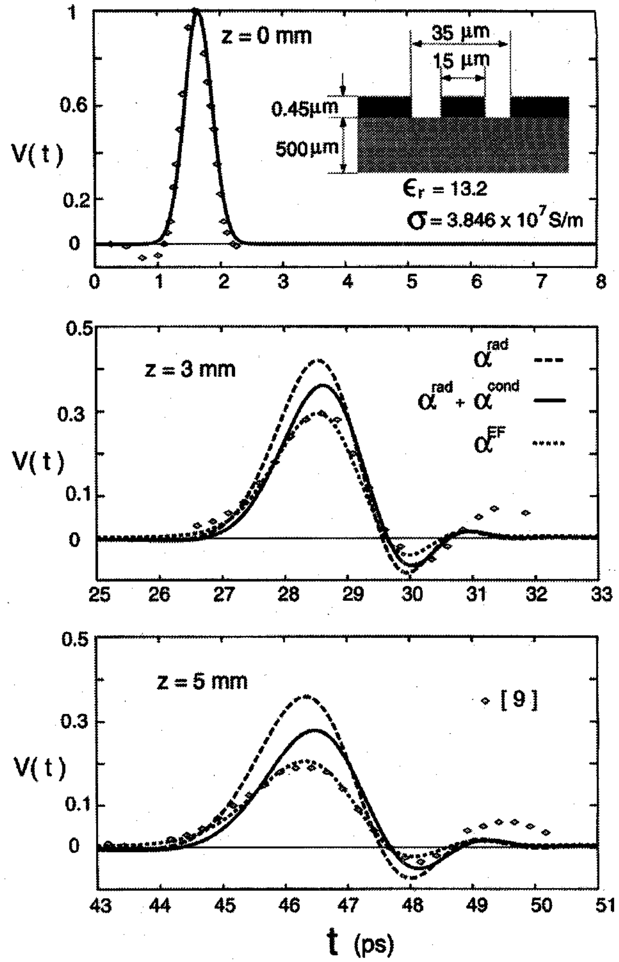


Fig. 5. Comparison of propagated Gaussian pulses by different empirical formulas and those by measurement.

The sum $(\alpha^{\rm rad} + \alpha^{cond})$ of empirical formulas (3) and (4) is inadequate in representing the more accurate one $\alpha^{\rm SDA}$ by the modified spectral-domain approach [14] as illustrated in Fig. 2. Instead of using α^{cond}, a new corrected term α^c is proposed so that it may better fit the difference curves for ($\alpha^{\rm SDA} - \alpha^{\rm rad}$). After carefully comparing the values for $\alpha^{\rm SDA}$ and $\alpha^{\rm rad}$, a new empirical formula for attenuation constant α^{EF} may be established for the coplanar waveguide shown in Fig. 1,

$$\alpha^{EF} = \alpha^{\rm rad} + \alpha^c \qquad \left(\frac{Np}{\rm mm}\right)$$

$$\alpha^c = \frac{g_1(k)}{(w+2s)} \cdot \left(\frac{f}{f_{te}}\right)^B \cdot \epsilon_r^{0.3} \cdot g_2(t) \cdot \left(\frac{\sigma}{\sigma_r}\right)^{-0.77} \tag{5}$$

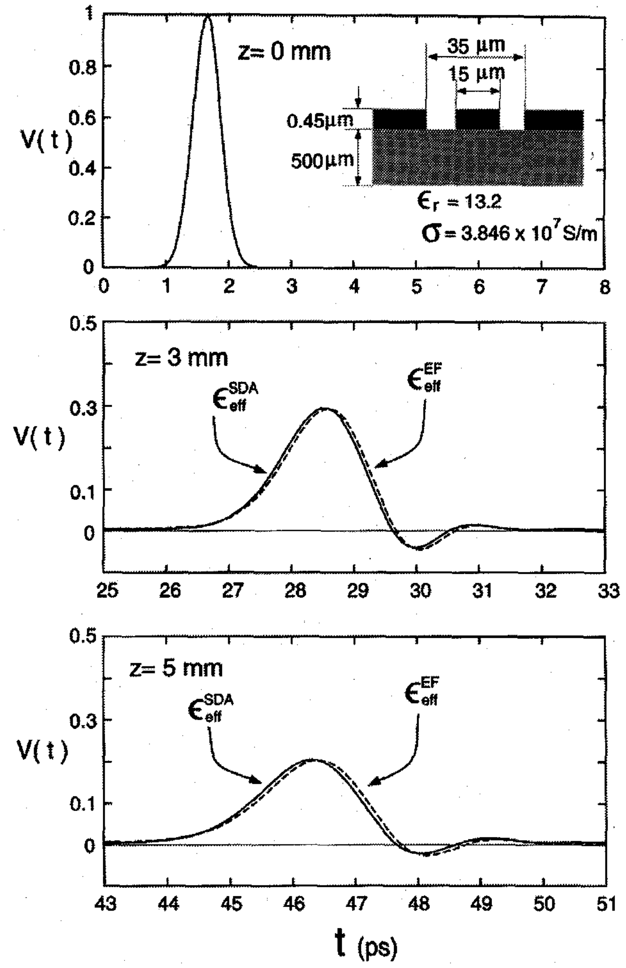


Fig. 6. Comparison of propagated Gaussian pulses based on accurate value $\epsilon_{eff}^{\mathrm{SDA}}$ and those based on empirical one ϵ_{eff}^{EF}.

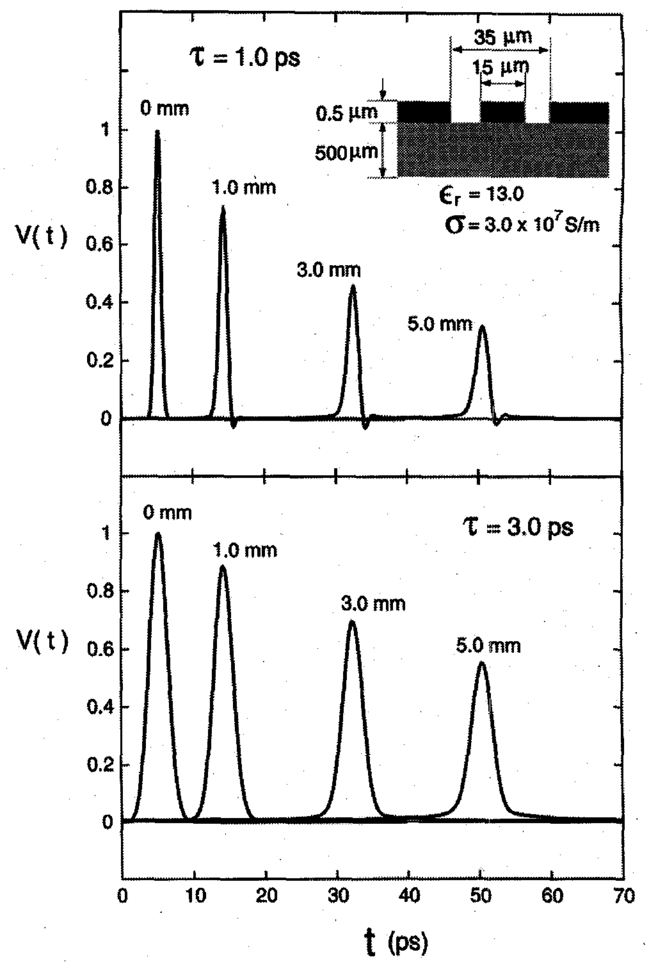


Fig. 7. Propagation of Gaussian pulses with propagation distance as parameters.

where $g_1(k) = 8.67k^2 - 7.82k + 4.17$, $g_2(t) = 0.01(t_r/t)^2 + 0.42(t_r/t) + 0.63$, $B = [0.25(t/t_r) + 0.14] \cdot (0.59k + 0.73)$, and $k = w/(w+2s)$. In (5), w and s are in μm, σ_r is 1.0×10^7 S/m, and t_r is 1.0 μm. Specifically, this formula has been verified to be acceptable, at least, for the following range of parameters

$$
\begin{aligned}
&0.4 < k < 0.7, && h > 5(w+2s) \\
&0.2 < \frac{t}{t_r} < 1.5, && 3 < \epsilon_r < 20 \\
&1 < \frac{\sigma}{\sigma_r} < 10, && f < 4f_{te}.
\end{aligned}
$$

III. Results

In this study, transient propagation characteristics of picosecond Gaussian and rectangular pulses along a lossy coplanar waveguide are investigated in detail. These pulses are analyzed based on the empirical formulas (2) and (5).

Fig. 2 compares the effective dielectric constants ϵ_{eff} and attenuation constants α of a coplanar waveguide based on accurate full-wave approach and approximate empirical formulas. With the presence of the internal inductance of the conductor, the effective dielectric constant $\epsilon_{eff}^{\mathrm{SDA}}$ by the modified spectral-domain approach [14] is somewhat different from the one ϵ_{eff}^{EF} by the empirical formula (2), especially in the lower frequency region. But this difference in $\epsilon_{eff}^{\mathrm{SDA}}$ and ϵ_{eff}^{EF} is not essential in affecting the transient behavior as illustrated in Fig. 6 and will be neglected in this study. The attenuation constant α^{EF} by new empirical formula (5) is compared with the one α^{SDA} by the modified spectral-domain approach [14]. Also included are the approximate one α^{rad} by (3) and the sum ($\alpha^{\mathrm{rad}} + \alpha^{cond}$) by (3) and (4) for comparison. Good fitting between the α^{EF} and α^{SDA} curves than the others suggests the use of the new empirical formula (5) in the subsequent analysis. Although the radiation formula α^{rad} shows good frequency-dependence behavior in the higher frequency range, it is inadequate in the lower frequency range in which the leaky wave is not excited. Again the sum ($\alpha^{\mathrm{rad}} + \alpha^{cond}$) is still not good in representing the full-wave one α^{SDA}.

To discuss the acceptable range of parameters for the formula (5), Fig. 3 compares of the attenuation constants α^{EF} by the new empirical formula (5) and the ones α^{SDA} by the modified spectral-domain approach [14] with the metallization thickness t and the substrate dielectric constant ϵ_r as parameters. Good fitting among the results further supports the use of the new attenuation empirical formula (5) in the time-domain analysis.

Shown in Fig. 4 are the results for α^{EF} and α^{SDA} but with the total width $(w + 2s)$ and the ratio $[w/(w + 2s)]$

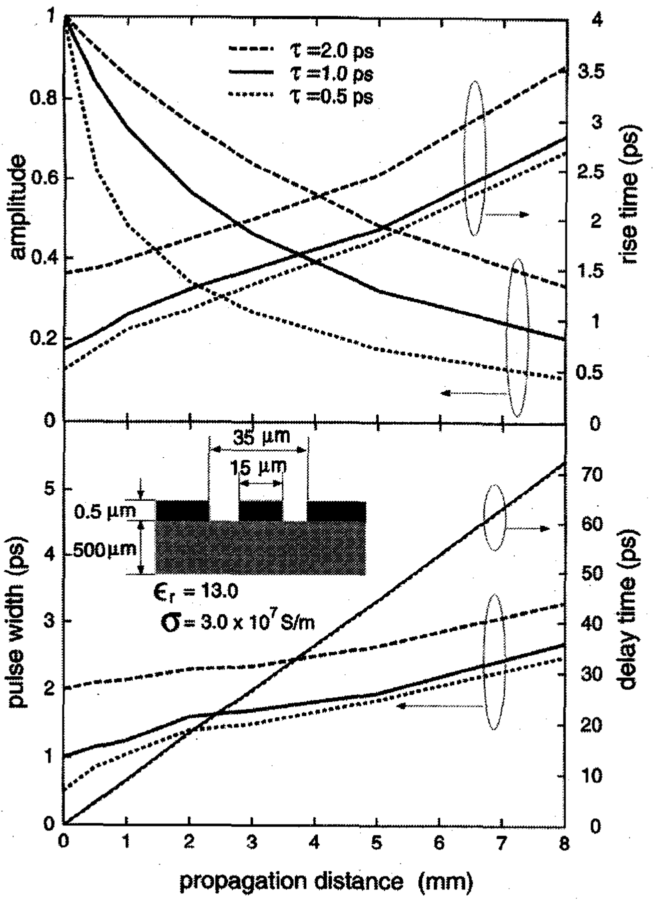


Fig. 8. Peak amplitude, pulse width, rise time, and delay time of Gaussian pulse versus propagation distance with input pulse width τ as parameters.

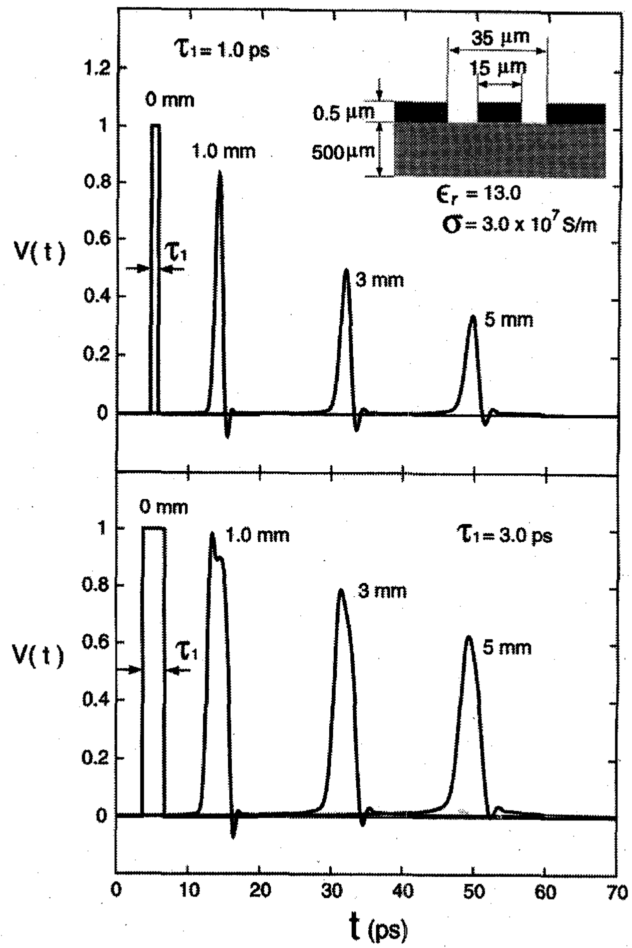


Fig. 9. Propagation of rectangular pulses with propagation distance as parameters.

as parameters. Note that as the total width $(w + 2s)$ is large, the leakage phenomenon would be more serious in high frequency, making the attenuation constant increase rapidly as the frequency increases.

Shown in Fig. 5 are the simulated propagating pulses at positions $z = 0$, 3 mm, and 5 mm by three different empirical formulas. Also included are the corresponding measured pulses by [9] for comparison. Here the input is a Gaussian pulse whose full width at half maximum (τ) is 0.52 ps. The new empirical formula α^{EF} in (5) is better than the others, α^{rad} and $(\alpha^{\text{rad}}+\alpha^{cond})$, as reflected by the good agreement with the experimental data. The empirical formula $(\alpha^{\text{rad}} + \alpha^{cond})$, the sum of (3) and (4), is relatively inadequate for time-domain propagation analysis.

Fig. 6 discusses the discrepancy of the propagated waveforms due to the difference in the effective dielectric constant ϵ_{eff}^{EF} by the empirical formula (2) and the one $\epsilon_{eff}^{\text{SDA}}$ by the modified spectral-domain approach [14]. Here, the solid lines show the waveforms based on the $\epsilon_{eff}^{\text{SDA}}$-curve and the dash lines show the ones based on the ϵ_{eff}^{EF}-curve. No significant discrepancy between these two waveforms suggests that the difference in $\epsilon_{eff}^{\text{SDA}}$ and ϵ_{eff}^{EF} may be neglected in the subsequent study.

Fig. 7 shows the transient Gaussian waveforms with propagation distance as parameters. Note that the tails of narrow pulses $(\tau = 1.0$ ps) show ripples while the wide pulses $(\tau = 3.0$ ps) do not. Physically, a broader frequency spectrum is associated with the narrow pulse whose lower frequency component has a phase velocity faster than the higher frequency component. The appearance of ripples in pulse tails is a consequence of this difference in phase velocities.

Shown in Fig. 8 are the useful parameters for characterizing the Gaussian pulse shape. Here, peak amplitude is defined as the maximum magnitude of a pulse and rise time is defined as the time duration between 10% of peak amplitude and 90% of peak amplitude. Pulse width is defined as the full width at half maximum and delay time is the time interval between the input pulse and the output pulse which has propagated a distance z. Note that the delay times are almost the same for the three pulses (i.e., τ = 0.5, 1.0, and 2.0 ps), but the dispersion and attenuation effects become serious as the pulse becomes narrower.

Fig. 9 shows the temporal propagation behavior as in Fig. 7 but with the rectangular pulse to replace the Gaussian pulse. When compared with Fig. 7, the rectangular pulse suffers from larger distortion as reflected by the fact that the wide rectangular pulse $(\tau_1 = 3.0$ ps) shows ripples in the pulse tails but the Gaussian pulse does not. Physically, the rectangular pulse has two sharp edges which lead to a broader frequency spectrum in Fourier analysis.

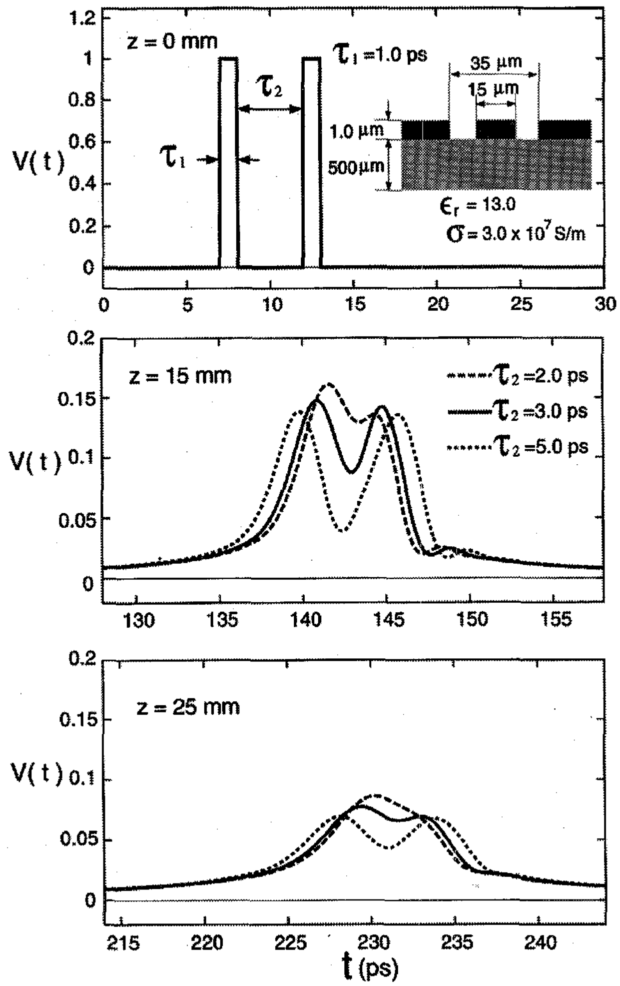


Fig. 10. Propagation of double rectangular pulses with pulse interval τ_2 as parameters.

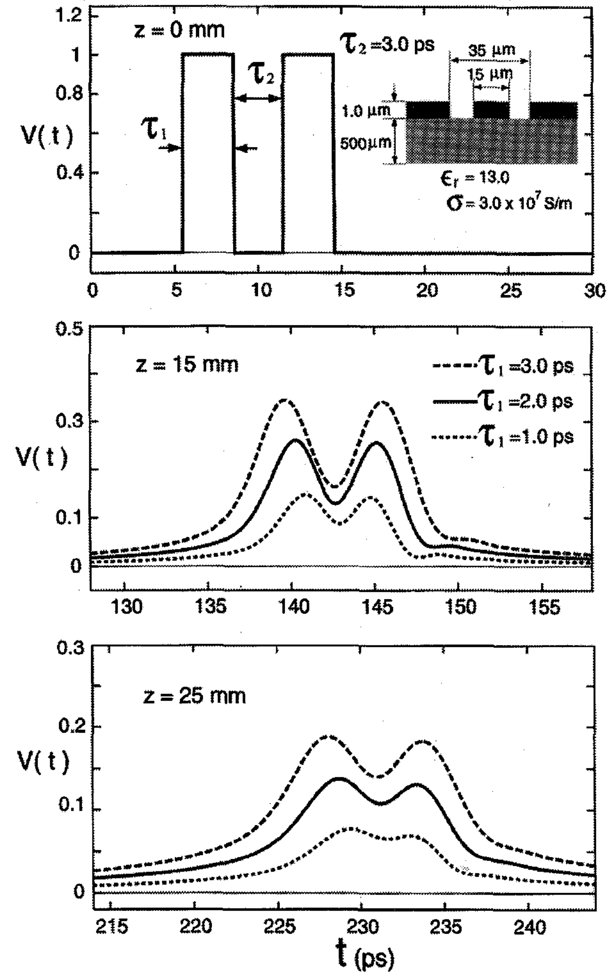


Fig. 11. Propagation of double rectangular pulses with input pulse width τ_1 as parameters.

The propagated waveforms associated with double rectangular input pulses are shown in Figs. 10 and 11. Fig. 10 shows the situation for which the input pulse width $\tau_1(=1.0$ ps) is fixed but the time interval τ_2 between pulses is changed. The double rectangular pulse with small τ_2 would be badly distorted, for instance, at $z = 15$ mm and eventually becomes a single pulse at $z = 25$ mm.

Propagation of double rectangular pulses with fixed time interval $\tau_2(=3.0$ ps) and variable input pulse width τ_1 is shown in Fig. 11. Again the two pulses almost merge into a single pulse as the input pulse becomes narrower. Although high speed circuits have a tendency of using pulses as narrow as possible, the waveguide attenuation and dispersion characteristics enforce a limit on the input pulse width and time interval.

IV. Conclusion

A new accurate empirical formula for attenuation constant has been proposed for analyzing the time-domain propagation phenomenon in a coplanar waveguide with finite metallization thickness and finite conductivity. By comparing with the experimental data, this new attenuation empirical formula has been proved to be adequate for time-domain analysis. In particular, the attenuation constants by this empirical formula and those by the modified spectral-domain approach have been compared and discussed in detail with metallization thickness t, substrate dielectric constant ϵ_r, total width $(w+2s)$, and the ratio $w/(w+2s)$ as parameters. Based on this new empirical formula, extensive propagation studies of picosecond Gaussian and rectangular pulses along a lossy coplanar waveguide have been presented. Although the internal inductance of imperfect conductors makes the accurate effective dielectric constant $\epsilon_{eff}^{\mathrm{SDA}}$ somewhat different from the empirical one ϵ_{eff}^{EF}, their difference is not important and may be neglected in the time-domain analysis. In this study, the transient propagation behaviors of double rectangular pulses along a lossy coplanar waveguide are also carefully examined.

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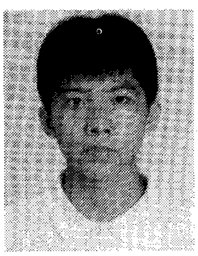

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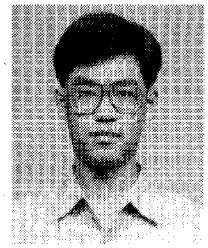

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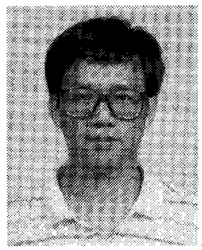

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In 1963, he joined the faculty of the Department of Electrical Engineering, National Taiwan University, where he is now a Professor. From August 1982 to July 1985, he was Chairman of the department. In 1974, he was a Visiting Researcher for one year in the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley. From August 1986 to July 1987, he was a Visiting Professor in the Department of Electrical Engineering, University of Houston, TX. In 1989, 1990, and 1994, he visited the Microwave Department, Technical University of Munich, Germany, Laboratoire d'Optique Electromagnetique, Faculte des Sciences et Techniques de Saint-Jerome, Universite d'Aix-Marseille III, France, and the Department of Electrical Engineering, Michigan State University, MI, respectively. His areas of interest include antenna and waveguide analysis, propagation and scattering of waves, and numerical techniques in electromagnetics.